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Preface

This volume, Proceedings of The 15th International Symposium on Operations Research, called SOR'19, contains papers presented at SOR'19 (http://sor19.fov.uni-mb.si/) that was organized by Slovenian Society INFORMATIKA (SDI), Section for Operations Research (SOR), University of Maribor, Faculty of Organizational Sciences, Kranj, Slovenia, and University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia, held in Bled, Slovenia, from September 25 to September 27, 2019. The volume contains blindly reviewed papers or abstracts of talks presented at the symposium.

The opening address at SOR'19 was given by Prof. Dr. Lidija Zadnik Stirn, President of the Slovenian Section of Operations Research, Mr. Niko Schlamberger, President of the Slovenian Society Informatika, Prof. Dr. Iztok Podbregar, Dean of the Faculty of Organizational Sciences, University of Maribor, Prof. Dr. Mitjan Kalin, Dean of the Faculty of Mechanical Engineering, University of Ljubljana, Prof. Dr. Immanuel Bomze, President of The Association of European Operational Research Societies (EURO),), Prof. Dr. Zrinka Lukać, President of Croatian Operational Research Society (CRORS), and presidents/representatives of some others Operations Research Societies from abroad.

SOR'19 is the scientific event in the area of operations research, another one in the traditional series of the biannual international OR conferences, organized in Slovenia by SDI-SOR. It is a continuity of fourteen previous symposia. The main objective of SOR'19 is to advance knowledge, interest and education in OR in Slovenia, in Europe and worldwide in order to build the intellectual and social capital that are essential in maintaining the identity of OR, especially at a time when interdisciplinary collaboration is proclaimed as significantly important in resolving problems facing the current challenging times. Further, by joining IFORS and EURO, the SDI-SOR agreed to work together with diverse disciplines, i.e. to balance the depth of theoretical knowledge in OR and the understanding of theory, methods and problems in other areas within and beyond OR. We believe that SOR'19 creates the advantage of these objectives, contributes to the quality and reputation of OR by presenting and exchanging new developments, opinions, experiences in the OR theory and practice.

SOR'19 was highlighted by five distinguished keynote speakers. The first part of the Proceedings SOR'19 comprises invited abstracts and papers, presented by five outstanding scientists: Acad. Prof. Dr. Ivan Bratko, Faculty of Computer and Information Science, University of Ljubljana, Ljubljana, Slovenia, Prof. Dr. Mirjana Čižmešija, University of Zagreb, Faculty of Economics and Business, Zagreb, Croatia, Assoc. Prof. Dr. Tibor Illés, Budapest University of Technology and Economics, Institute of Mathematics, Budapest, Hungary, Prof. Dr. Joanna Józefowska, Poznan University of Technology, Poznan, Poland (the EURO plenary), and Prof. Dr. Matej Praprotnik, Laboratory for Molecular Modeling, National Institute of Chemistry, Ljubljana, Slovenia.

Proceedings includes 106 papers or abstracts written by 203 authors. Most of the authors of the contributed papers came from Slovenia (79), then from Croatia (43), Czech Republic (13), Hungary (12), Slovak Republic (12), Poland (9), Austria (7), Spain (5), France (4), Netherlands (3), Portugal (3), Italy (2), Norway (2), Romania (2), Thailand (2), Germany (1), Indonesia (1), Ireland (1), Serbia (1), and United Kingdom (1). The papers published in the Proceedings are divided into Plenary Lectures (5 abstracts), seven special sessions: Application of Operation Research in Agriculture and Agribusiness Management (5 papers), Formal and Behavioral Issues in MCDM (6 papers and 1 abstract), Graph Theory and

Algorithms (11 papers and 1 abstract), High-Performance Computing and Big Data (4 papers), Optimization in Human Environments (7 papers), System Modelling & Soft Operational Research (5 papers), Towards Industry 4.0 (5 papers), and eight sessions: Econometric Models and Statistics (10 papers), Environment and Social Issues (5 papers and 1 abstract), Finance and Investments (11 papers), Location and Transport, Graphs and their Applications (4 papers), Mathematical Programming and Optimization (7 papers and 2 abstracts), Multi-Criteria Decision-Making (6 papers), Human Resources (4 papers), and Production and Management (6 papers).

The Proceedings of the previous fourteen International Symposia on Operations Research organized by the Slovenian Section of Operations Research, that are listed at https://www.drustvo-informatika.si/sekcije/sor/sor-publikacijepublications/, are indexed in the following secondary and tertiary publications: Current Mathematical Publications, Mathematical Review, Zentralblatt fuer Mathematik/Mathematics Abstracts, MATH on STN International and CompactMath, INSPEC. The Proceedings SOR'19 are expected to be covered by the same bibliographic databases.

The success of the scientific events at SOR'19 and the present proceedings should be seen as a result of joint effort. On behalf of the organizers we would like to express our sincere thanks to all who have supported us in preparing the event. We would not have succeeded in attracting so many distinguished speakers from all over the world without the engagement and the advice of active members of the Slovenian Section of Operations Research. Many thanks to them. Further, we would like to express our deepest gratitude to prominent keynote speakers, to the members of the Program and Organizing Committees, to the referees who raised the quality of the SOR'19 by their useful suggestions, section's chairs, and to all the numerous people - far too many to be listed here individually - who helped in carrying out The 15th International Symposium on Operations Research SOR'19 and in putting together these Proceedings. Last but not least, we appreciate the authors' efforts in preparing and presenting the papers, which made The 15th Symposium on Operations Research SOR'19 successful.

We would like to express a special gratitude to The Partnership for Advanced Computing in Europe (PRACE) for a financial support and to The Association of European Operational Research Societies (EURO) for financing the EURO plenary speaker.

Bled, September 25, 2019

Lidija Zadnik Stirn
Mirjana Kljajić Borštnar
Janez Žerovnik
Samo Drobne
Janez Povh
(Editors)

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ON THE COMPLEXITY OF A FILTERING PROBLEM FOR CONSTRAINT PROGRAMMING: DECOMPOSITION BY THE STRUCTURE OF PERFECT MATCHINGS

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Abstract: A complexity analysis based on the structure of perfect matchings is given for the most efficient basic filtering algorithms in constraint programming with respect to the role of edges in matchings.

Keywords: constraint programming,matching theory, decomposition theory

1 INTRODUCTION

In matching theory it is a basic problem to determine all the edges in a given graph which can be extended to a maximum matching. Such edges are called maximally matchable or allowed edges. Apart from the graph theory community (see e.g [11]), researchers in constraint programming have also investigated this problem (cf. [3,4, 12]). The motivation for studying the question from constraint programming point of view is originating from certain constraint propagation methods ([12]), where the applied filtering algorithmic scheme is based on the above question. In this paper we will study the efficient algorithms for perfect matchings only with respect to the above problem, which is related to the symmetric alldiff constraint introduced in [12]. However, as it was shown in [4], the scheme of constraint propagation based on perfect matchings can be extended to a more general framework.

As a main result of [4] a decomposition algorithm was worked out for identifying the allowed edges. In this paper we will give a detailed running time analysis for the decomposition algorithm presented in [4]. It turns out that the complexity bound given in that paper is not precise.

The organization of this paper is as follows. In Section 2 we will present the necessary formal background on matching theory. We collect here some basic material needed later on and include contents of almost all the required results. In Section 3 we analyze the iterative version of the algorithm to compute the category of edges into mandatory (covered by all perfect matchings), allowed and forbidden (i.e. not allowed). The obtained results are mainly based on the Structure Theorem of Gallai & Edmonds. In Section 4 an algorithm using divide-and-conquer paradigm is analyzed. Finally, in Section 5 we will give a short conclusion. Because of space constraints proofs are omitted.

2 MATCHING THEORY AND STRUCTURAL DECOMPOSITION

In this paper we will consider undirected general graphs and our main focus will be on graphs with perfect matchings. Our terminology will be standard, the set of vertices and set of edges will be denoted by *V(G)* and *E(G)*, respectively. . A good reference for any undefined terms is [10].

---

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We will call an edge of a graph G *allowed* if it occurs in some maximum matching (respectively, perfect matching, if exists) and any edge which is not allowed will be called *forbidden*. An edge which belongs to every maximum (respectively, perfect) matching will be called *mandatory*.

A graph G with a perfect matching is said to be *elementary* if its allowed edges form a connected spanning subgraph of G. A *matching covered* graph is an elementray graph without forbidden edges.

Let M be a maximum matching of G. An edge $e \in E(G)$ is said to be *M-positive* if $e \in M$, otherwise e is called M-negative. An *M-alternating path* in G is a path stepping on M-positive and M-negative edges in an alternating fashion.

The deficiency of G denoted by $\delta(G)$ is defined as the number of vertices left unmatched by a maximum matching. A graph G is said to be *factor-critical* if $\delta(G-x)=0$ for every $x \in V(G)$. Maximum matchings of factor-critical graphs are called *near-perfect matchings*.

The bipartite graph $G = (V_1 \cup V_2, E)$ has positive surplus (viewed from V_1) if $|\Gamma(X)| > |X|$ for all $\emptyset \neq X \subseteq V_1$, where $\Gamma(X)$ denotes the set of neighbours of X. Bipartite graphs with positive surplus are connected.

For a general graph $G = (V, E)$ we define subsets $A(G)$, $C(G)$ and $D(G)$ of $V(G)$ as follows:

$D(G) = \{$the set of vertices in G not covered by at least one maximum matching of $G\}$,
$A(G) = \Gamma(D) \setminus D(G)$,
$C(G) = V(G) \setminus (A(G) \cup D(G))$.

The following theorem (see e.g. [10]) is fundamental in the structure theory of matchings.

Theorem 1 (Gallai-Edmonds Structure Theorem). *If G is a graph and $A(G)$, $C(G)$ and $D(G)$ are defined as above, then the following statements hold:*

1. *The components of the subgraph induced by $D(G)$ are factor-critical,*
2. *The subgraph induced by $C(G)$ has a perfect matching,*
3. *The bipartite graph obtained from G by deleting the vertices of $C(G)$ and the edges spanned by $A(G)$, and by contracting each component of $D(G)$ to a single vertex has positive surplus (when viewed from $A(G)$),*
4. *Every maximum matching of G contains a perfect matching of each component of $C(G)$, a near-perfect matching of each component of $D(G)$, and a complete matching from $A(G)$ into distinct components of $D(G)$.*

The decomposition has the following properties:

- Edges spanned by $A(G)$ are forbidden
- Edges connecting $A(G)$ to $C(G)$ are forbidden
- Every edge incident with a vertex of $D(G)$ is allowed
- There is no edge between $C(G)$ and $D(G)$
- Vertices of $A(G)$ and $C(G)$ are vital
- Vertices of $D(G)$ are allowed
- Each connected component of $C(G)$ has even cardinality
- Each connected component of $D(G)$ has odd cardinality

Note that every component of $G[C]$ has a perfect matching, the bipartite subgraph $G[A, base(D)]$ obtained from G by deleting edges spanned by $A(G)$ and by contracting each component of $D(G)$ to a single vertex has a complete matching from $A(G)$ to $D(G)$, and every connected component of $G[D]$ has a near-perfect matching.

A set X of vertices in G is *extreme* if $\delta(G-X) = \delta(G) + |X|$. In [4] a general pruning routine was introduced to aid in the investigation of extreme sets of graphs which have perfect matchings. It was also shown that finding an extreme set can be accomplished in linear time. The algorithm of [4] is an iterative graph decomposition method by which we can mark the forbidden edges with taking advantage of the structure provided by the decomposition. In each step maximal extreme sets of the subgraphs obtained by the previous steps of the algorithm are determined and some edges are marked as forbidden according to the structure defined by the extreme sets. Using the structure with respect to the extreme sets new subgraphs are defined and the iteration is continued.

The decomposition method is based on the following theorem [4].

Theorem 2. *Let $G = (V, E)$ be any graph with a perfect matching M, $x \in V$, and let (D, A, C) be the Gallai-Edmonds canonical decomposition of $G-x$. Then the following statements hold:*

1. *The set $X = A \cup \{x\}$ is extreme in G,*
2. *Edges spanned by X or joining X with C are forbidden,*
3. *The bipartite graph G_0 obtained from $G-C$ by contracting each connected component of D to a single vertex and by deleting each edge spanned by X has a perfect matching,*
4. *Edges belonging to all, some (but not to all) or none of perfect matchings in the bipartite graph G_0 are, respectively, edges belonging to all, some (but not to all) or none of perfect matchings in G.*
5. *The graph G_i obtained from $G-C$ by contracting the set $V(G)-D_i$ to a single vertex has a perfect matching,*
6. *The mandatory, allowed, or forbidden edges of G are precisely those edges which are, respectively, mandatory, allowed, or forbidden in one of the graphs G_i, $i = 0, \ldots, t$, where $t = |X|$.*

In the next two sections we will present and analyse the "pure iterative" and the "divide and conquer" strategy of the decomposition method. In Section 3 we will consider the naïve approach for identifying forbidden edges with the help of maximal extreme sets. In this case we will make use of the properties of maximal extreme sets as direct consequences of its definition. We will show that this algorithm provides an improved worst-case running time, then the previously developed methods [11,12] which could ensure $O(|V|\cdot|E|)$ only. In Section 4 the algorithm of [4] will be presented and by detailed running time analysis we will show that the divide and conquer strategy is more efficient than the pure iterative approach.

3 PURE ITERATIVE ALGORITHM

The following is the pure iterative version of the decomposition algorithm:

Algorithm 1 The iterative approach to determine the partition of edges

```
Require: General graph $G = (V, E)$ with an initial perfect matching $M$
Ensure: Partition of edges
  while there are UNSCANNED vertices in $G$ do
    Select one UNSCANNED vertex $x$
    Relabel $x$ as SCANNED
    Compute the maximal extreme set $X$ in $G - x$ (see algorithm in [2, Section 2.1])
    Let $(A, C, D)$ be the Gallai-Edmonds Decomposition after the last step of the previous routine
    Mark all edges spanned by $X$ as forbidden
    Form the gluing bipartite graph $G_0$ with bipartition $(X, base(D_i))$
    Let $M_0 \leftarrow M \cap E(G_0)$
    Determine the partition of edges in $G_0$ with respect to $M_0$ (s. Algorithm 2 in [3])
    Mark all vertices of $X$ as SCANNED
  end while
```

The crucial point in the analysis of the above algorithm is the number of the required iterations. It is clear that the number of iterations are related to the number of maximal extreme sets.

However, according to [2, Theorem 2.1] the problem of finding the maximum Tutte set, and thus the maximum extreme set is intractable. This means that in general there may exist exponential number of maximal extreme sets. To demonstrate this fact with a very simple example consider the graph consisting of K_2 and n triangles *0* attached to one of its endpoints. It is easy to check that such a graph has 2^n maximal extreme sets. In order to overcome this drawback we introduce the following new concepts.

Definition 1 (Elementary extreme set). *An extreme set, such that each element of it belongs to the same elementary component.*

In general, the number of maximal elementary extreme sets in a non-elementary graph is lower than the number of maximal extreme sets in its elementary components. The similar holds true when we remove the forbidden edges: the number of extreme sets in matching covered graphs maybe greater than the number of extreme sets in elementary components. The following result about maximal elementary extreme sets was proved by Bartha & Kŕesz [1].

Theorem 3. *Let G be a graph with a perfect matching. The maximal elementary extreme sets of G form a partition on $V(G)$.*

Therefore, extending the concept of [10] from elementary graphs, maximal elementary extreme sets will be called *canonical classes*. The set of all canonical classes will be denoted by *P(G)*. The following result from [13] clarifies the number of maximal extreme sets in a non-elementary graph.

Theorem 4. *Any maximal extreme set of a non-elementary graph is the union of some maximal elementary extreme sets***.**

The following concept is equivalent to the one of “strong proof” by Király [5].

Definition 2 (Extreme closure) *For any vertex u, the extreme closure of u, denoted by Ext(u), is the intersection of all maximal extreme sets containing u.*

As a straightforward consequence of Theorem 4, *Ext(u)* can be also characterized with canonical classes.

Proposition 1. *Ext(u) is a union of some canonical classes.*

Corollary 1. *$Ext(u)$ can be found in linear time for each $u \in V(G)$.*

Now let *Ext(G)* denote the set of distinct extreme closures of *G*.

Theorem 5. *There is a one-to-one correspondence between Ext(G) and P(G); consequently $|Ext(G)| = |P(G)|$ holds.*

During the algorithm we identify the forbidden edges spanned by *A(G)* and between *C(G)* and *A(G)*. Next we build the gluing bipartite graph and perform alternating depth-first search starting from the color class *X* and a free edge. It is necessary since considering only canonical classes is not satisfactory to find the partition of edges (it can happen that the forbidden edge lies between two different maximal elementary extreme sets).

Theorem 6. *Let* $p=|Ext(G)|$ and $m=|E(G)|$. Then *Algorithm 1 uses maximum p iteration steps, consequently the upper bound for the pure iterative algorithm is* $O(p \cdot m)$.

4 DIVIDE AND CONQUER STRATEGY

Recall that the algorithm developed in [4] is based directly on Theorem 2. It uses a divide-and-conquer paradigm which is a natural consequence of the result.

The procedure first constructs a perfect matching in a given general graph, then decomposes the graph, according to the Gallai-Edmonds Structure Theorem (Theorem 1) and successively identifies allowed edges and eliminates forbidden edges reducing the remainder graph in a suitable way. The method is summarized as *Algorithm 2*.

The goal is now to determine the running time of this algorithm. For this first we review some concepts from [1].

Let C be an elementary component and M be a perfect matching. Then a *C-ear* is an M-alternating path α connecting two vertices of C such that no vertex of α, other than its endpoints, lies in C. It is easy to see that a **C**-ear starts and ends with an **M**-negative edge. Furthermore, it can be shown (cf. [1]) that the existence of a C-ear is independent from the choice of the matching M.

We say that elementary component C' is *two-way accessible* from component C, in notation $C\rho C'$, if C' is covered by a C-ear. It was shown in [1] that the reflexive and transitive closure ρ^* *of* ρ is a partial order on the set of elementary components. For a similar approach see also [6].

Now let us introduce some new concepts.

Definition 3. ***Let*** *$C_0,C_1,...,C_k$ be distinct elementary components of G such that $C_0\rho C_1\rho C_2\rho ...\rho C_k$. Then we say that $(C_0,C_1,...,C_k)$ forms a ρ-chain. Moreover, let $P(C_0,C_1,...,C_k)$ denote the set of canonical classes of the elementary components forming the chain. The canonical length of $(C_0,C_1,...,C_k)$ is given by $|P(C_0,C_1,...,C_k)|-1$. Finally,* ***t****he canonical diameter of G is the maximum canonical length concerning all ρ-chains in G.*

Algorithm 2 The divide-and-conquer approach to determine the partition of edges

```
Require: General graph $G = (V, E)$ with an initial perfect matching $M$
Ensure: Partition of edges
  if $/V/ = 2$ then {base case}
    Mark vertices in $V$ as SCANNED
    if $/E(G)/ = 1$ then
      Mark edge in $E$ as mandatory
    else
      Mark edge in $E$ as allowed
    end if
    return
  end if
  Select one UNSCANNED vertex $x$
  Relabel $x$ as SCANNED
  Compute the Gallai-Edmonds Decomposition $(A, B, C, D)$ of $G-x$ (s. Algorithm 1 in [4])
  Let $X \leftarrow A \cup \{x\}$ {extreme set}
  Mark all edges spanned by $X$ as forbidden
  Mark all edges between $X$ and $C$ as forbidden
  if $/C(G-x)/ > 0$ then
    Find connected components $C_1, C_2, \ldots, C_k$ of $G[C]$
    for every connected component $C_i$ do
      Let $M_i \leftarrow M \cap E(C_i)$
      Recursive call of this procedure with $G = C_i$ and $M = M_i$
  end for end if
  Form the gluing bipartite graph $G_0$ with bipartition $(X, B \cup base(D_i))$
  Let $M_0 \leftarrow M \cap E(G_0)$
  Determine the partition of edges in $G_0$ (s. Algorithm 2 in [3])
  Remove forbidden edges from $G$
  Mark all vertices of $X \cup B$ as SCANNED
  Mark all edges in $G_0$ as TRAVERSED
  Mark vertices incident with all TRAVERSED edges as SCANNED
  Let $t$ be the number of connected components of $G[B \cup D]$, i.e. $t \leftarrow /X/$
```

```
if $|D(G-x)| > 0$ then
  Form the pieces $G_1, G_2, \ldots, G_t$ of $G$ at extreme set $X$
  for every piece $G_i$ with at least one UNSCANNED vertex do
    Let $M_i \leftarrow M \cap E(G_i)$
    Recursive call of this procedure with $G = G_i$ and $M = M_i$
  end for
end if
```

Now using the above concepts, we are ready to give the complexity analysis of Algorithm 2.

Theorem 7. *Let $m=|E(G)|$ and let λ denote the canonical diameter of graph G with perfect matchings. Then Algorithm 2 uses maximum λ iteration steps, consequently the upper bound for the divide and conquer strategy is $O(\lambda \cdot m)$.*

As a final result we show that the improvement of the complexity with the divide and conquer strategy can be expressed formally by the parameters used for the analysis of Algorithms 1 and 2.

Theorem 8. *Let p_{min} denote the cardinality solution of the minimum set cover for Ext(G), i.e. the minimum number of sets of Ext(G) the union of which covers V(G). Then $\lambda \leq p_{min}$, where λ denotes the canonical diameter of G.*

5 CONCLUSION

In this paper we have provided a detailed analysis of the state-of-the-art filtering algorithms for constraint propagation with respect to the role of edges in perfect matchings. We could characterized the worst-case complexity of both the pure iterative method and the divide-and-conquer strategy with graph parameters defined by the matching structure. With the help of this concept, we have shown formally that the divide-and-conquer strategy is indeed more efficient than the pure iterative algorithm.

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Appendix

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